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PERMEAMETER FOR HIGH-TEMPERATURE MAGNETIC MEASUREMENTS

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16\. Abstract
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SUMMARY

A new permeameter measures the magnetizing force and the corresponding magnetic induction of a specimen up to 1000° C in a vacuum or an inert atmosphere. Two massive symmetrical yokes close the magnetic path around the specimen which consists of a rod of solid material or a bundle of sheet material. The yokes are made of a specially processed alloy of 9 percent iron, 91 percent cobalt, a high-temperature soft magnetic material. A coil surrounding the specimen supplies a magnetizing force of up to 100 oersteds (8000 A/m). A separate coil is used to measure the magnetic induction. Auxiliary coils provide additional magnetizing force resulting in a longitudinal distribution of flux uniform to within 1 percent in the specimen. The magnetizing force is calculated from the coil current while a fluxmeter is used for the induction. The null balance type permeameter uses the magnetic potentiometer principle with yoke compensating coils to cancel the effects of the reluctance of the yoke and the joint gaps. Very close agreement was obtained at room temperature when compared to the MH type permeameter. The effect of temperature on the normal induction curves for the yoke material is also presented.

INTRODUCTION

The requirement of the space program for high temperature power conversion equipment has revived interest in the accurate measurement of properties of magnetic materials at high temperatures. Two of the National Bureau of Standards (NBS) permeameters, the Sanford-Winter MH (ref. 1) and the Fahy Simplex (ref. 2), are not easily adapted to high temperatures. A high-temperature (HT) null-type permeameter has been developed, which, unlike either of the NBS permeameters uses a magnetic potentiometer (refs. 3 and 4) with a magnetic core.

It is the purpose of this report to (1) describe the new permeameter, (2) compare its performance at room temperature to the NBS permeameter and (3) illustrate its use by showing the effect of temperature on the normal induction curves for a 9 percent iron, 91 percent cobalt alloy.

DESCRIPTION

The new permeameter (fig. 1) measures the magnetizing force and the corresponding magnetic induction of the specimen up to 1000° C in a vacuum or an inert atmosphere. The specimen is a solid rod or a bundle of sheet material up to 1.27-centimeter wide and 0.317-centimeter thick with a minimum length of 16.5 centimeters. The central and end coils are wound on alumina bobbins that surround the specimen. All coils have a rectangular cross section and are made by slipping short sections of alumina tubing over nickel wire.

The magnetizing force is supplied by the H coil which is approximately $7\frac{1}{2}$ centimeters long and has 57 turns of wire. The value of induction is obtained from the 102 turn B coil.

The end auxiliary magnetizing coils, which are electrically and magnetically in series with the H coil, provide an additional magnetizing force resulting in a longitudinal distribution of flux uniform to within 1 percent in the sample.

Two massive symmetrical yokes close the magnetic path around the specimen. To minimize the introduction of undesirable stresses into the specimen, most of the weight of the upper yoke is supported by the central coil alumina bobbin. Each yoke is approximately $16\frac{1}{2}$ centimeters long and consists of a 26 turn compensating coil wound on a magnetic core. The core is a 9 percent iron, 91 percent cobalt high-temperature soft magnetic alloy (ref. 6) made from electron beam zone refined starting materials, alloyed by arc melting, and rolled to 0.028-centimeter-thick sheet. The symmetrical construction of the yokes promotes uniform flux distribution throughout the cross section of the specimen.

The magnetic potentiometer is a 106 turn coil wound on a magnetic semicircular core. The core consists of seven $2\frac{1}{2}$-centimeter-wide layers of the same alloy as used in the yokes. The ends of the magnetic strips are extended to the specimen surface through cutouts in the alumina bobbin. The use of the magnetic core reduces the number of turns when compared to the air core magnetic potentiometer, which makes it practical for high temperatures.

THEORY OF OPERATION

Permeability is usually calculated from the normal induction curve (p. 6 or ref. 5). This curve is obtained by measuring the maximum induction B and the corresponding magnetizing force H while the material is subjected to symmetrical magnetic cycling.

The value of induction is obtained from a flux measuring device such as a fluxmeter or a ballistic galvanometer. For either instrument, the reading is proportional to

$$\int_{t_1}^{t_2} e\,dt \tag{1}$$

By Faraday's law,

$$\int_{t_1}^{t_2} e\,dt = 2N_1\Phi \tag{2}$$

for symmetric cycling where Φ is the total flux in maxwells and N_1 is the number of turns in the B coil. Since the cross-sectional area of the B coil is larger than the area of the specimen, a correction has to be made to the value of the total flux. It has been shown (p. 14 of ref. 5) that the induction can be written

$$B = \frac{\Phi}{A} - \left(\frac{\alpha - A}{A}\right)\mu_o H = \mu H \tag{3}$$

where H is the magnetizing force in oersteds, α the effective area of the test coil in square centimeters, and A the area of the specimen in square centimeters. The value of α was determined experimentally.

In order to examine the role of the magnetic potentiometer in the determination of H, let us call the part of the specimen between the magnetic potentiometer extensions in figure 2 the active part of the specimen L. By Ampere's circuital law,

$$\left[\int H \cdot dl\right]_{\substack{\text{active part}\\ \text{of specimen}}} + \left[\int H \cdot dl\right]_{\substack{\text{magnetic}\\ \text{potentiometer}}} = 0.4\,\pi N_2 I \tag{4}$$

where I is the magnetizing current in amperes, dl the differential length in centimeters, and N_2 the number of turns in the H coil. Let the direction of the magnetic field associated with equation (4) be indicated by the solid arrows in figure 2. Suppose now that the compensating coils provide a magnetomotive force (MMF) such as to oppose the MMF in the magnetic potentiometer (second term in eq. (4)). This condition will also aid the MMF along L (first term in eq. (4)). This can be seen by observing the direction of the compensating magnetic field as shown by the dotted arrows in figure 2. If the value of compensating current is adjusted so that the second term of equation (4) becomes zero, then

$$H = \frac{0.4\,\pi N_2 I}{L} \tag{5}$$

when H is uniform. The H coil supplies a magnetizing force of up to 100 oersteds (8000 A/m).

The second term in equation (4) is monitored by a flux measuring device connected to the magnetic potentiometer terminals. When there is no deflection on the instrument, then by an equation similar to equation (2) the flux is zero within the magnetic potentiometer coil. Since the flux is proportional to the permeability times the magnetizing force, H in the magnetic potentiometer is zero and the second term in equation (4) is also zero.

The electrical circuit is a modification of the usual ballistic measurement method (ref. 7). In figure 3 the specimen magnetically couples the series connection of the end auxiliary magnetizing and H coils with the B coil. The dc source E_1, variable resistor R_1, ammeter A, and the magnetizing current reversing switch S_1 are connected to the auxiliary and H coils. The compensating coils are connected to the dc source E_2, the variable resistor R_2 through reversing switch S_2. Switch S_1 is ganged to switch S_2 so that the two circuits are switched simultaneously. Switch S_3 is connected to the B coil through the left hand terminals and to the magnetic potentiometer through the right hand terminals. The center connection of S_3 is made to the flux measuring device M. With S_3 in the right hand position R_2 is adjusted until M shows no deflection while S_1 and S_2 are reversed back and forth. The circuit is now in balance. Switch S_3 is then placed in the left hand position and B and H are measured using equations (3) and (5). The current through the ammeter is I in equation (5).

The major sources of instrument error associated with the measurement of B are the fluxmeter, the uncertainty of the cross sectional area of the coil, and the nonuniformity of the flux. The accuracy of the fluxmeter is 1 percent of its reading. The effect of coil area error is approximately 1 percent for materials with permeability greater than 100. With a flux uniformity of 1 percent the overall accuracy of B is approximately 3 percent. An additional 1 percent should be added to this figure at high temperatures to account for the changes in the coil area with temperature.

As can be seen from equation (5), the accuracy of H depends on the magnetizing current and the uncertainty of the length L. Due to the finite width of the magnetic potentiometer core L is known to only approximately 3 percent. With the current usually measured to better than 0.1 percent the overall accuracy of H is also approximately 3 percent.

With any null balance instrument there exists the uncertainty of the null. When the permeameter is in balance H is repeatable to within ±0.01 oersted.

PERFORMANCE

The room temperature performance of the HT null-type permeameter was compared to the MH permeameter. The specimen was a solid bar of type C1020 carbon steel, a material selected for its machinability and moderate permeability. The specimen was sent to the Materials Research Institute at NBS for calibration on their MH permeameter. The normal induction curve data points for each instrument are plotted in figure 4. As can be seen very close agreement was obtained. The maximum deviation between the two curves is within 2 percent.

The permeameter was used to show the effect of temperature on the normal induction curve of the 9 percent iron, 91 percent cobalt alloy, the core material used in the magnetic potentiometer and the yokes. The magnetizing force was in the direction of rolling. In figure 5 the initial 25° C curve was measured in the as-rolled condition. The final 25° C curve illustrates the improvement in permeability obtained after one annealing run.

CONCLUSION

The new permeameter provides a means of making magnetic measurements at high temperatures. When the magnetic potentiomenter principle is used, the effects of the reluctance of the yoke and the joint gaps are eliminated. When compared to the standards laboratory permeameter, very close agreement was obtained at room temperature.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, December 7, 1971,
112-27.

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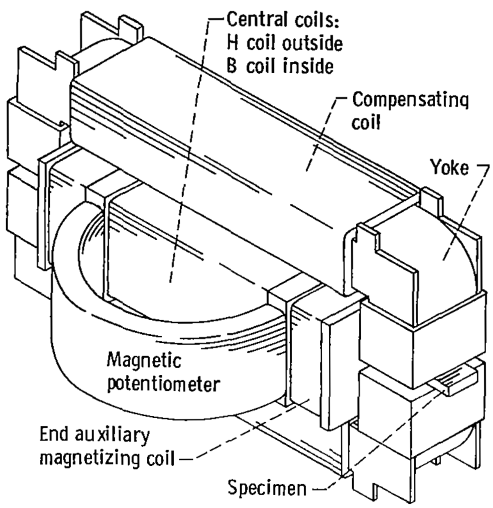

Figure 1. - HT null-type permeameter.

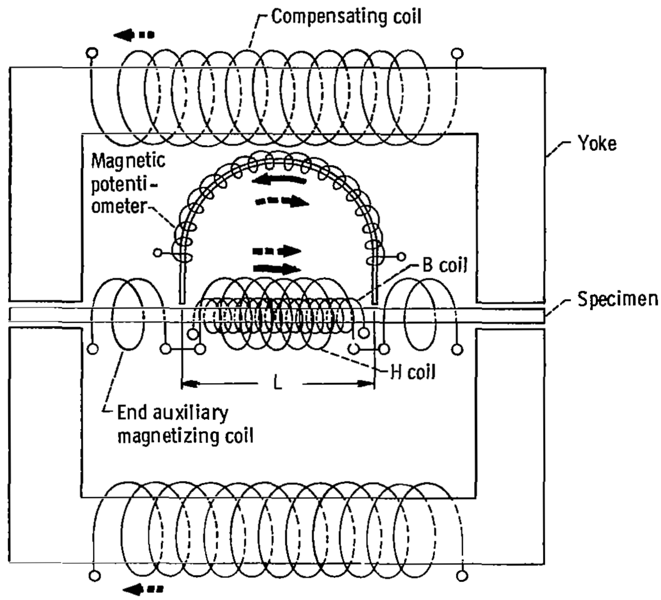

Figure 2. - Magnetic schematic of HT null-type permeameter.

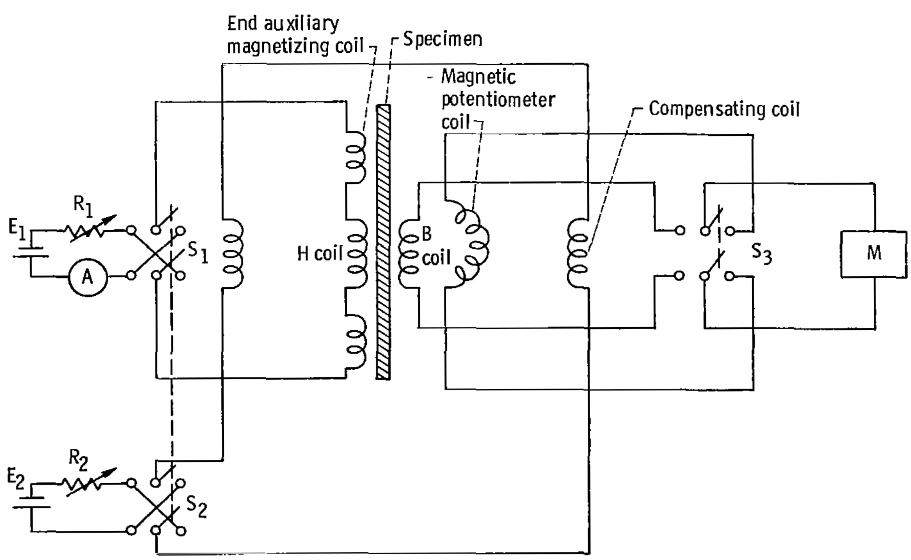

Figure 3. - Electrical circuit schematic for B and H measurements of high-temperature null-type permeameter.

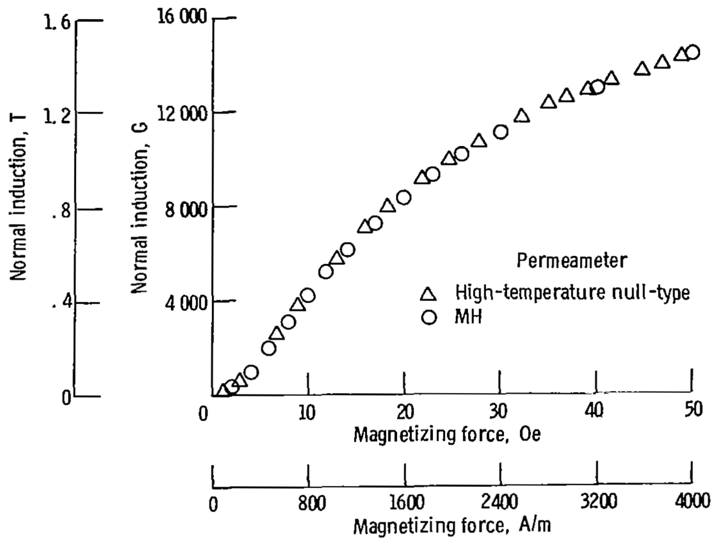

Figure 4. - Comparison of HT null-type and MH permeameters for C1020 carbon steel.

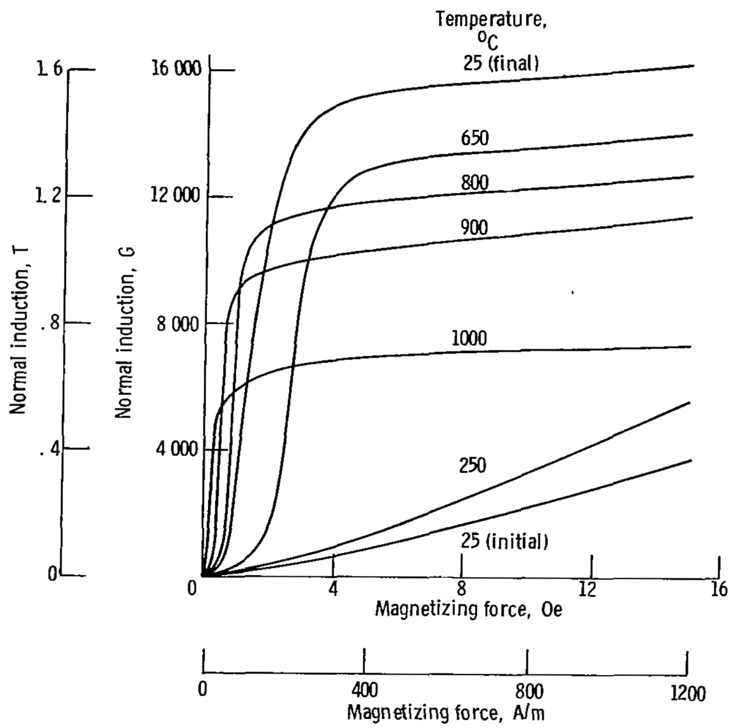

Figure 5. - Effect of temperature on normal induction curve of the 9 percent iron, 91 percent cobalt alloy with the magnetizing force in the direction of rolling.

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